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Foundational Aero Research for Development of Efficient Power Turbines with 50% Variable-speed Capability

by Gerard E. Welch, Gary J. Skoch, and Douglas R. Thurman

ARL-MR-0768 February 2011

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14. ABSTRACT Mission studies have shown strong potential to reduce in-theater casualties by using high-speed rotorcraft capable of both vertical takeoff and landing (VTOL) and high-speed, high-altitude, long-range cruising. The rotational speed of the prop-rotors on this type of vehicle must be slowed during forward flight to maintain high propulsive efficiency. One approach to meeting this requirement is to use a variable-speed power turbine (VSPT) to drive the prop-rotor. However, power turbines run most efficiently at high-speed and within a narrow speed range. The research and technology development effort described herein was funded by the U.S. Army Research Laboratory's (ARL) Director's Research Initiative award to develop the technology foundation needed for power turbines that operate efficiently over a speed range that may vary by as much as 50%. Results from this technology development effort are reported. Major barriers to VSPT operation and the approach selected for VSPT design are discussed. Results from the computational analysis and design system that has been assembled and validated are presented along with preliminary designs for VSPT incidence-tolerant blade sections. Technology transfer and future plans and collaborations, including performance evaluation using a turbine cascade and test rig or engine evaluations, are also discussed.					
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1. Objective

The need for increased military and civilian rotorcraft lift capability is evidenced by the ever-increasing payload capabilities of growth versions of existing helicopters (e.g., the Army CH-47F, the Navy CH-53K, and the civilian S-92). Additionally, mission studies for the next generation of vertical takeoff and landing (VTOL)-capable, heavy-lift, long-range (>2000 nm), tilt-rotor vehicles—for example, future Joint Multi-Role (JMR) vehicles and the National Aeronautics and Space Administration (NASA) Large Civil Tilt Rotor (LCTR)—reveal that, for maximum efficiency of operation, high-speed (Mn 0.5), high altitude (30,000 ft) flight during the cruise leg of the missions is essential (Kiger, 2008; Johnson, 2005; Acree et al., 2008, 2010). To achieve high efficiency at both the hover near ground and high-speed forward flight, the speed of the main rotor must be varied substantially—ideally, turning only half as fast at cruise conditions as compared to hover. This requirement poses a severe challenge for the turboshaft engines, which nominally operate efficiently over a narrow speed range (Sculley, 2008; D'Angelo, 1995; Snyder and Thurman, 2009).

The main rotor speed variation required for fuel-efficient cruise can be achieved by using a multi-speed transmission driven by a fixed-speed power turbine. Alternatively, the main rotor speed variation can be achieved by using a variable-speed power turbine (VSPT) driving a fixed-speed transmission. The increase in fuel burn from the added weight and complexity of a multi-speed transmission can be traded against the capabilities and efficiency penalties of a VSPT. Indeed, a combination of turbine speed change and variable transmission may prove optimal. The present research topic was focused on achieving main rotor speed variation by power-turbine speed variation alone (i.e., assuming a fixed transmission).

Key objectives of this effort are to develop the aero technology foundation for enabling efficient wide variable-speed power turbine operation and demonstrate the performance potential via validated computational analyses. To enable 50% power-turbine speed variation, the power-turbine rotor blades must be tolerant to wide variations in inlet flow angle (i.e., incidence-tolerant blading). However, this wide operability is obtained at the price of increased design-point loss levels.

Mission studies for notional heavy lift vehicles, such as the Army Highly Efficient Tilt Rotor (HETR) concept, indicated the vehicle would be powered by four 12,000 to 14,000 shaft horse-power (SHP) turboshaft engines with expected power turbine adiabatic efficiencies on the order of 90% due, in part, to engine size. Therefore, a specific objective of this effort is to demonstrate via validated computational analyses a 50% VSPT with ≥88% adiabatic efficiency at both high and low speeds in smaller size class engines. Additionally, the high-altitude (35,000 ft) cruise operation considered in some engine studies (Sculley, 2008) requires the power turbine to operate at a low Reynolds number. At low Reynolds numbers, the flow can be transitional and

more prone to separation than in typical rotorcraft operation. An additional key objective, therefore, is to assess the lapse in turbine efficiency with altitude associated with the low Reynolds number effects.

2. Approach

The critical aerodynamic technical challenges to be overcome in the development of wide variable-speed power turbines are the incidence-tolerant rotor blade and exit guide vanes, the impact of low Reynolds numbers, and attainment of high efficiency at high aerodynamic loading levels. The incidence-tolerant rotor will entail low reaction blading, which operates at high work factor and positive incidence at its mission cruise condition (50% speed); a lower work factor and high negative incidence at takeoff; and contingency power conditions (100% speed). A variable exit guide vane blade row, which does not exist in currently fielded power turbines, is required to de-swirl the flow discharged from the last rotor.

Development of a vehicle for the LCTR mission described by Johnson et al. (2005) and Acree (2008, 2010) is a goal of the NASA Fundamental Aeronautics Program (FAP). The key mission points include takeoff and altitude operation with the main rotor and VSPT at 100% speed (100% N_{PT}) and the altitude cruise operation point where the main rotor and VSPT speeds are reduced to 54% (54% N_{PT}). The challenges of accomplishing the NASA mission exclusively with VSPT technology are significant. Collaboration was established between the Vehicle Technology Directorate (VTD) field element and the NASA LCTR project to leverage NASA funds and expertise and take advantage of the work already done by NASA in defining a set of mission requirements and corresponding technical challenges.

The following work elements are on schedule for developing the aero technology foundation for a wide speed range VSPT. The goals are to attain ≥88% adiabatic efficiency at 100% and 50% speed, takeoff, and cruise conditions, respectively, and assess the lapse in turbine performance associated with low Reynolds numbers at cruise altitude in a linear cascade with upstream throttle and altitude exhaust capabilities that allows assessment of blade performance at flight Mach and Reynolds numbers.

2.1 FY10–11

The following are the objectives for fiscal year (FY) 2010–2011:

- Define engine requirements that match the LCTR mission requirements. A notional 7500 SHP engine was defined. The engine is intended to be consistent with the Army Aviation Applied Technology Directorate (AATD) Future Affordable Turbine Engine (FATE) but is at a lower technology level.

- Conduct conceptual design of VSPT to meet LCTR engine requirements. Assess design-point (54% N_{PT}) and off-design (100% N_{PT}) performance levels.
- Conduct detailed aero-design of blading for candidate VSPT stage. Analyze design-point and off-design performance for comparison with mean-line code.

2.2 FY11-12

The following are the objectives for FY11–12:

- Test candidate blade/vane concept over a range of incidence, inlet turbulence intensities, and Reynolds numbers, and use data to validate computational fluid dynamic (CFD) predictions.
- Update loss versus incidence models in turbine design tools and then redesign the power turbine (PT) for 50% variable speed capability with inclusion of any benefits from flow path and three-dimensional (3-D) blade design concepts to achieve best efficiency.
- Verify, via validated CFD predictions, the performance goal of $\geq$88% adiabatic efficiency for take-off and cruise conditions.

3. Results

3.1 Conceptual Design

3.1.1 Obtain Existing Relevant PT Flow Path Geometry and Relevant Design Parameters (e.g., power requirements, flow rate)

The VSPT requirements were set by mission analyses conducted by Snyder and Thurman (2009). The engine requirements are provided in table 1. The engine operates at 7500 SHP at sea level, standard day. The engine size accounts for contingency power and one-engine-inoperative requirements. The required power level changes with mission point; however, the specific power—power to mass flow rate—or enthalpy extraction across the power turbine is essentially constant (near 200 SHP/lb_m/s) throughout the mission. This highlights a key challenge for the VSPT. The required enthalpy extraction is constant, while the PT shaft speed changes by a nearly 50%. The change from 100% N_{PT} at take-off to 54% N_{PT} at cruise requires that the flow turning in the rotors blade rows must increase by a factor of 2 and the turbine work factor, ψ, must increase by a factor of 4. For a given geometry, the aerodynamic loading increases in proportion with the work factor. Retention of high turbine efficiency at the extremely high (ψ = 3 to 3.5) work factors, and aero-loading levels, of cruise operation is one of the principal challenges for the VSPT for the LCTR-like missions.

Table 1. VSPT requirements at key flight points of LCTR mission (Snyder and Thurman, 2009).

Flight Point	Takeoff	Cruise	Cruise	Cruise	Cruise
Altitude (kft)	2	28	28	28	28
VSPT Speed ($N/N_{100\%}$) (%)	100	54	61.5	75	100
Main-rotor Tip-speed (ft/s)	650	350	400	500	650
Power (SHP)	4593	2328	2330	2329	2330
VSPT Mass Flow Rate (lb_m/s)	22.03	12.22	11.71	11.63	11.55
Specific Power (SHP/lb_m/s)	208.5	190.5	200.2	200.2	201.8
PT Inlet Temperature ($T_{4.5}$) (R)	2204	1812	1798	1795	1818
PT Inlet Pressure ($p_{0,4.5}$) (psia)	58.0	26.76	26.3	26.1	26.6
PT pressure Ratio (total-to-total)	4.04	5.34	5.25	5.21	5.30
Corrected Flow (lb_m/s)	11.51	12.54	12.41	12.18	11.95
Corrected Speed ($Nc/Nc_{100\%}$)	102.3	60.8	69.7	85.1	112.7
Aft-stage Unit-Re (in^{-1})[a]	50,000	30,000	30,000	30,000	30,000

[a]Based on static conditions at last stage rotor exit with $M_{r,2} = 0.7$.

3.1.2 Conduct Conceptual Design Studies of Candidate Incidence Tolerant Rotor Blading/Exit Guide Vane Concepts and Technologies for a Fixed Flow Path

The turbine meanline design system of F. Huber (Florida Turbine Technology), provided by Dr. John P. Clark as part of the Air Force Research Laboratory (AFRL) Turbine Design and Analysis System (TDAAS), was used to design the turbine flow path at the conceptual level, and analyze design and off-design performance. The meanline code is consistent with a meanline code developed under this Director’s Research Initiative (DRI), which is based on the methodology of Ainley and Mathieson (1957), Dunham and Came (1970), and Kacker and Okapuu (1982) (referred to herein as AMDCKO). The design was conducted at 54% N_{PT} and at the 28-kft cruise altitude. Off-design performance at 100% N_{PT} at both take-off (2 kft) and 28 kft (before transition) was accepted. Based on operability considerations, a four-stage turbine design was selected with aerodynamic loading levels (Zweifel) of Z = 1.0 to 1.1 and a mechanical constraint of AN^2 = 45 E9 $rpm^2 \cdot in^2$.

Example meanline results for design point and off-design are shown in figure 1. Note that the results from the TDAAS are in agreement with the in-house AMDCKO code and the earlier VSPT study results of D’Angelo (1995). Three- and four-stage VSPT designs were achieved at design-point efficiencies above 88% (goal) at work factors above 3. Note that the off-design

performance levels (100% N_{PT} take-off) are predicted to be higher than at the more highly loaded design-point (cruise) condition (54% N_{PT} cruise).

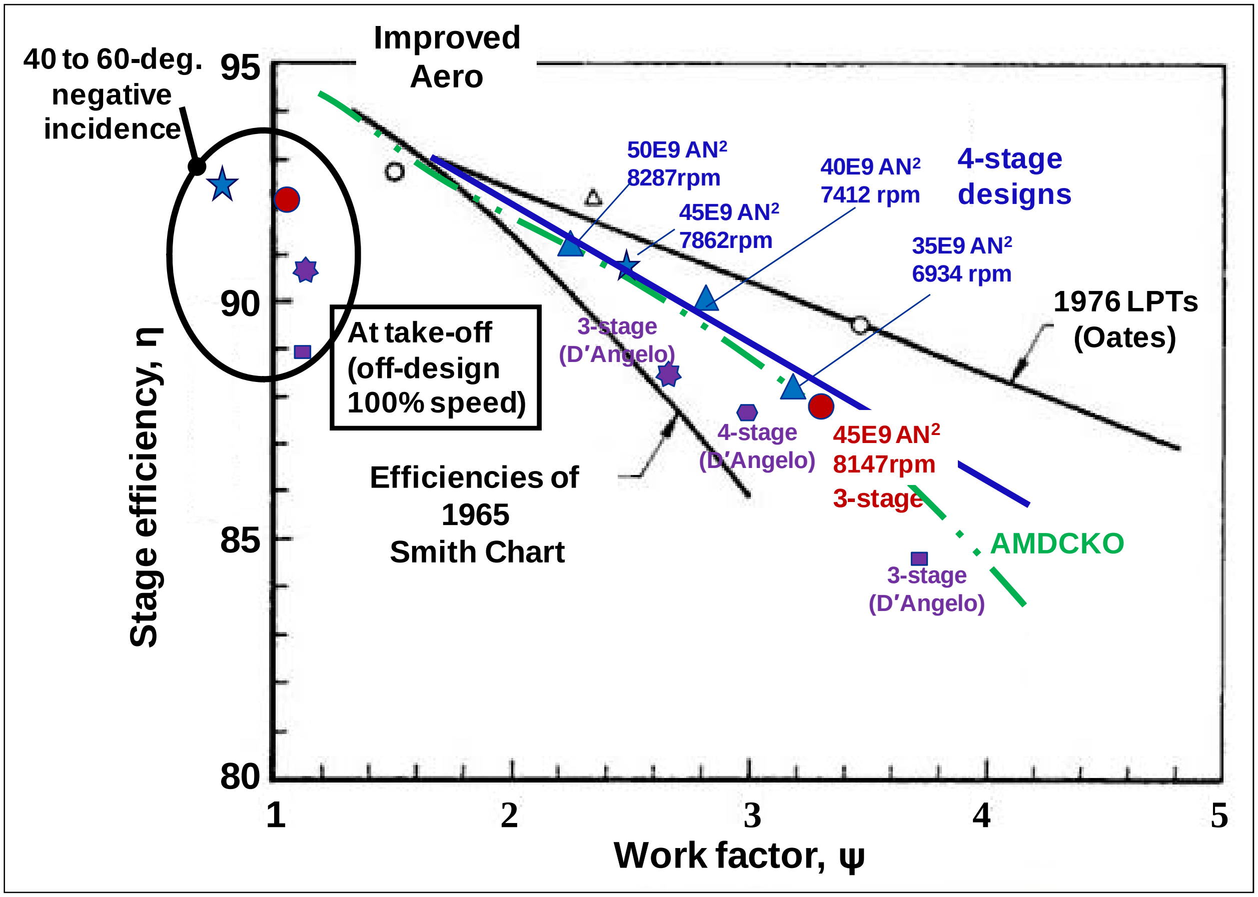


Figure 1. Turbine design-point stage efficiency versus work factor ($\Delta h_0/U^2$), showing data from Smith (1965), low-pressure turbine (LPT) data compiled by Oates (1976), VSPT conceptual designs by D'Angelo (1995), VSPT conceptual designs for LCTR (AFRL TDAAS), and AMDCKO meanline results (NASA ARL-VTD/NASA in-house). Select off-design (100%-speed) efficiencies are shown for reference in the oval.

3.1.3 Predict/Assess Loss Versus Incidence Characteristics of Most Promising Candidate Blade/Vane Concepts with Validated CFD

The aerodynamic technical challenges of the VSPT were summarized by Welch (2010) based on a review of the literature and analyses conducted during this study on two-dimensional (2-D) blade sections of state-of-the-art LPT blading obtained from Dr. John P. Clark of AFRL. The blading had similar turning requirements as the VSPT blading for the LCTR from the meanline designs (above) as seen in table 2. Particular attention was paid to the impact of Reynolds number lapse from sea level to cruise altitude on incidence range and loss levels.

Table 2. Design-point flow angles and loading for three- and four-stage rotors ($AN^2 = 45 \times 10^9$ $rpm^2 \cdot in^2$ and ultra-high loading L1-series blading (Clark et al., 2009).

	Three-stage			**Four-stage**			**L1M**[a]			**L1A**[a]		
Zweifel	1.0			1.0			1.34			1.34		
Rotor	β_1	β_2	**Turn**	β_1	β_2	**Turn**	β_1	β_2	**Turn**	β_1	β_2	**Turn**
1	55	-65	120	53	-67	120	35	-60	95	35	-60	95
2	50	-58	108	56	-66	122						
3	29	-42	70	46	-57	102						
4	--	--	--	28	-39	66						
h/c_x R1	2.54			2.36								
h/c_x R_{Nstg}	3.77			4.01								

[a]AFRL ultra-high-load blade shapes provided by Dr. J. P. Clark (AFRL).

3.1.4 Impact of Low Reynolds Number

A high cruise altitude requirement, such as the 28 kft expected cruising altitude of the LCTR aircraft, imposes a larger Reynolds number variation (ground to cruise) on the power turbine than encountered in conventional (<15 kft) rotorcraft operation. The estimated aft-stage unit-Reynolds-numbers (see section 3.1.1) are approximately 50,000/in. and 30,000/in. at takeoff and cruise altitudes, respectively. The 7500-SHP-class blading is expected to have axial chords near 1 in, leading to chord Reynolds numbers associated with transitional suction-sides (Haselbach et al., 2002, and Praisner et al., 2007).

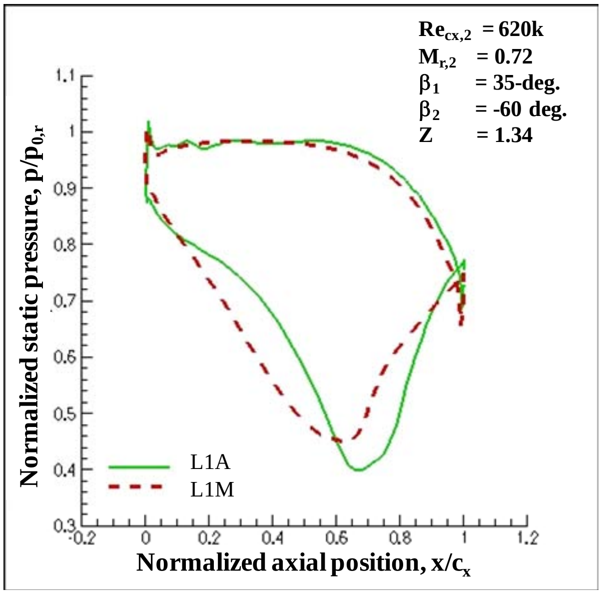
3.1.5 Design-point Efficiency Lapse With Reynolds Number

The loss in design-point performance with altitude due to transitional flow is expected to be analogous to that experienced by larger low pressure turbines of modern turbofans (e.g., Hourmouziadis [1989], Haselbach et al. [2002], and Gier et al. [2008]). The absolute change in Reynolds number will be lower—less variation in pressure from sea-level-static (SLS) to 28 kft

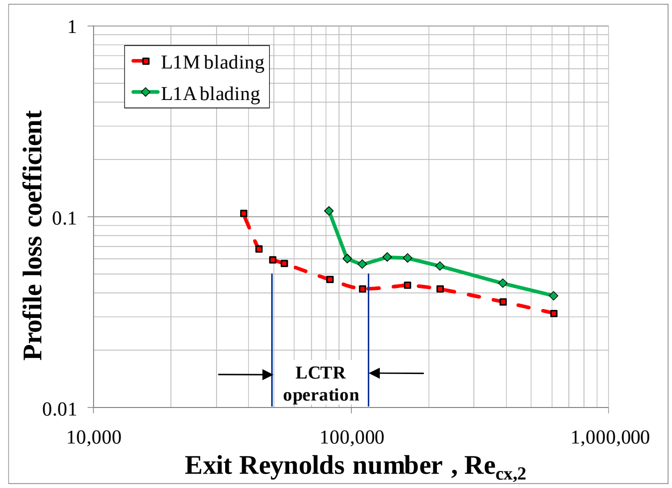
as compared to SLS to 40 kft—but the variation will occur at lower aft-stage chord Reynolds numbers (60k to 100k). The need to run at all conditions above the point at which the airfoil stalls, after which loss coefficients rise precipitously, may ultimately set the axial chord of the VSPT blading (Riegler and Bichlmaier, 2007). An increase in axial chord, though consistent with reduced blade count, leads to increased length-per-stage and ultimately increased engine length (weight and packaging). Gier et al. (2008) have argued convincingly, counter to recent trends toward ultra-high aerodynamic loading ($Z > 1.3$), to use moderate aerodynamic loading levels ($0.8 < Z < 1$). The optimum loading levels for the LCTR-class turbines are expected to emerge over time as industry, labs, and academia apply component and engine-level preliminary design/optimization tools to the problem.

The impact of low Reynolds number is firstly a design-point problem, affecting all future turbines of this size class and mission—variable or fixed speed. Computed Reynolds number lapse for AFRL L1A and L1M high lift blades (Clark et al., 2009) are provided in figure 2a. The L1-series has Zweifel coefficients at $Z = 1.34$ and 95° of turning. The blades are considered to be relevant to embedded stages of the LCTR VSPT. The computations were performed using Chima's 2-D Reynolds-Averaged Navier-Stokes (RANS) code (Chima, 1987) and Wilcox's low-Re variant of the $\kappa-\omega$ model (Wilcox, 1994). The inlet turbulence intensity was set at 5% and the length scale of turbulence was set to achieve the desired freestream turbulent viscosity. The length scale of turbulence selected strongly affected the location of transition on the suction side. The C-grids used were generated using the Grids About Airfoils Using Poisson's Equation (GRAPE) code (Sorenson, 1980). The grid spacing was set so that the y^+ near the leading edge at high chord $Re_{cx,2}$ (620k) was less than two.

The computed loading diagrams and Reynolds number lapse for the L1A and L1M blade profiles are shown in figure 2b. The blades accomplish the same 95° flow turning, at the same aerodynamic loading level, using mid- and aft-loaded sections (figure 2a). The loading distribution has an impact on the increase in loss with decreasing chord Reynolds number, though the power-law lapse rates in the fully turbulent ($Re_{cx,2} > 200k$) region are similar.



a. Loading diagrams for L1A (aft-loaded) and L1M (mid-loaded) ultra-high lift LPT blades.[22]



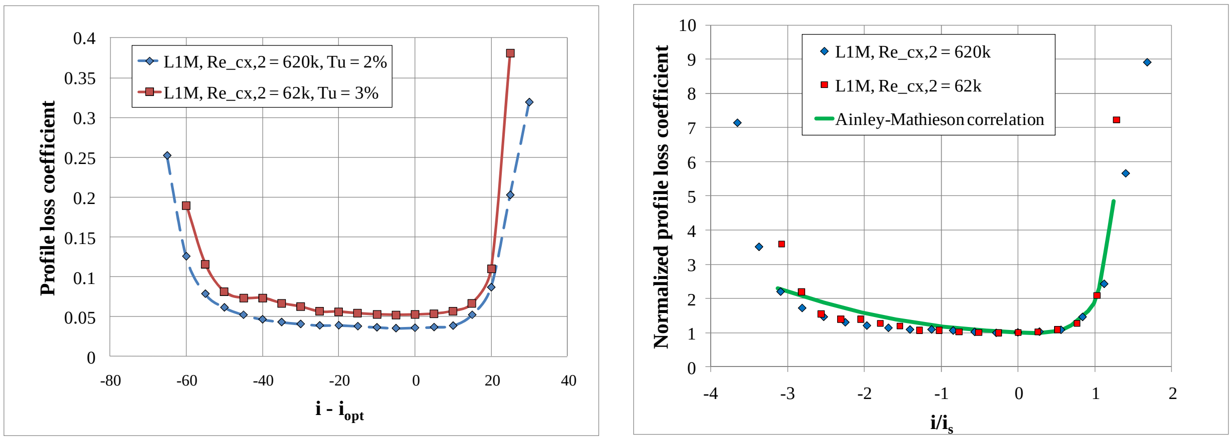
b. Profile loss coefficient as a function of $Re_{cx,2}$ for L1A and L1M LPT blades.[22]

Figure 2. Computed loading diagrams and Reynolds lapse rates for aft- (L1A) and mid-loaded (L1M) LPT blading (Clark et al., 2009; reference 22 in Welch, 2010) accomplishing the same 95° flow turning at high aerodynamic loading (Z = 1.34).

3.1.6 Impact of Re-lapse on Incidence Range

The need for strong incidence-tolerance exacerbates the low-Re challenge. In addition to increased minimum loss, the loss buckets will generally narrow as Reynolds number is reduced. This impact was analyzed using the L1M high lift (Z = 1.34) blading. The reduction in incidence range with decreasing $Re_{cx,2}$ is evident in figure 3a. The minimum loss increases with decreasing Reynolds number (increasing altitude, see figure 2b) and the loss bucket narrows measurably (figure 3a). The canonical form of the loss bucket (figure 3b) is largely retained at the two Reynolds numbers and is in good agreement with the off-design correlation of Ainley and Mathieson, (1955).

The AMDCKO meanline analysis shows that incidence range decreases, as expected, with increased loading (or reduced axial-chord to pitch ratio for a given turning). In addition to minimizing design-point loss due to Reynolds number lapse, there is a justifiable argument to restrict aerodynamic loading levels (Z) to obtain increased incidence range as well.



a. Loss as a function of incidence.

b. Ainley and Mathieson[16] normalized loss as a function of normalized incidence.

Figure 3. Computed 2-D profile (+ shock) loss coefficients as a function of incidence for L1M blading[22] at $Re_{cx,2}$ = 620k and 62k and $M_{r,2} = 0.72$: (a) loss bucket; and (b) normalized, showing comparison with Ainley-Mathieson incidence correlation (1955; reference 16 in Welch, 2010).

3.2 Detailed Aero Design

The detailed aerodynamic was conducted using the AFRL TDAAS system, the Wand grid generator and Leo RANS solver of AeroDynamics Solutions, Inc. (ADS) and NASA in-house grid generation tools and RANS solvers. The 2-D blade profiles at hub, mid-span, and tip sections were set in AFRL TDAAS using the blade generation tool (Huber). The tool uses 19 bases to describe a turbine blade: 7 of the 19 bases are non-uniform rational b-spline (NURBS) control points and the remainder are parameters that are used in standard industry practice to describe turbine blades (e.g., leading and trailing edge thickness, leading edge wedge angle, uncovered turning). The TDAAS system is Matlab based and facilitates Department of Energy (DOE) and gradient-search optimization.

After a 2-D section is generated within the blade generation software, the Wand/Leo codes of ADS generated 2-D steady solutions for the boundary conditions prescribed. After the sections are designed, they are stacked on radial lines in TDAAS to generate 3-D blade coordinates. Then, 3-D single-block grids were generated using Turbomachinery C-GRID (TCGRID) (Chima, 2003). Computations are conducted using the SWIFT RANS mixing-plane solver (Chima, 2003) with Wilcox's low-Re κ–ω model (Wilcox, 1994).

3.2.1 3-D Flow Field at Design-point Operation

An example result for design-point operation of stage 1 blading is provided in figure 4. The strong secondary flow fields associated with the high aerodynamic loading and turning levels of the cruise (design) operating point are evidenced by the accumulation of high-loss (entropy) flow in select regions. The low-momentum flow (aero-blockage) in these regions were generated elsewhere—at the endwalls and regions of separation—and transported by secondary-flow to

regions of low static pressure. The influence of the strong secondary flow fields in resetting the spanwise velocity triangles presents a key challenge during the design process.

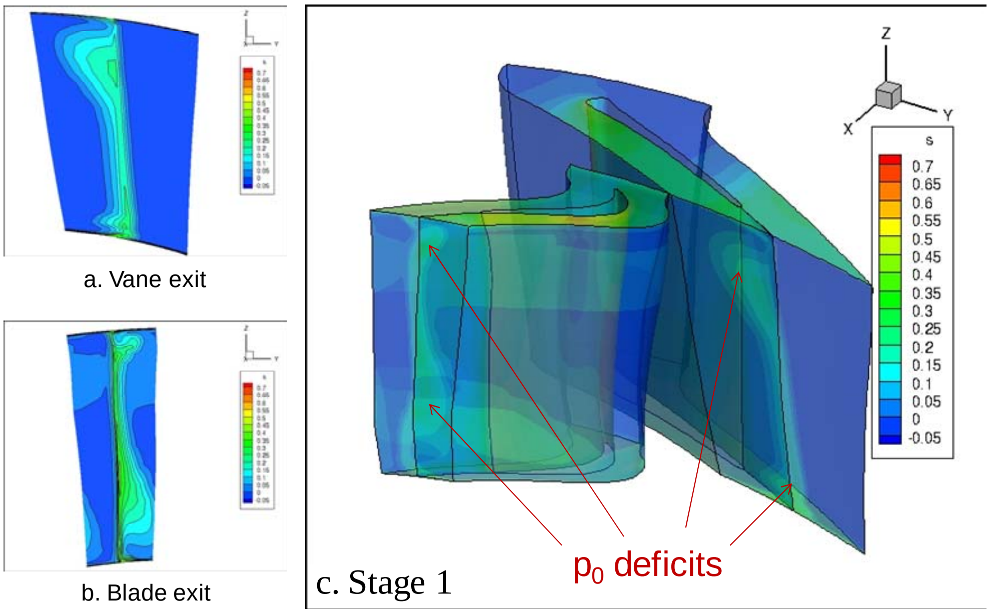


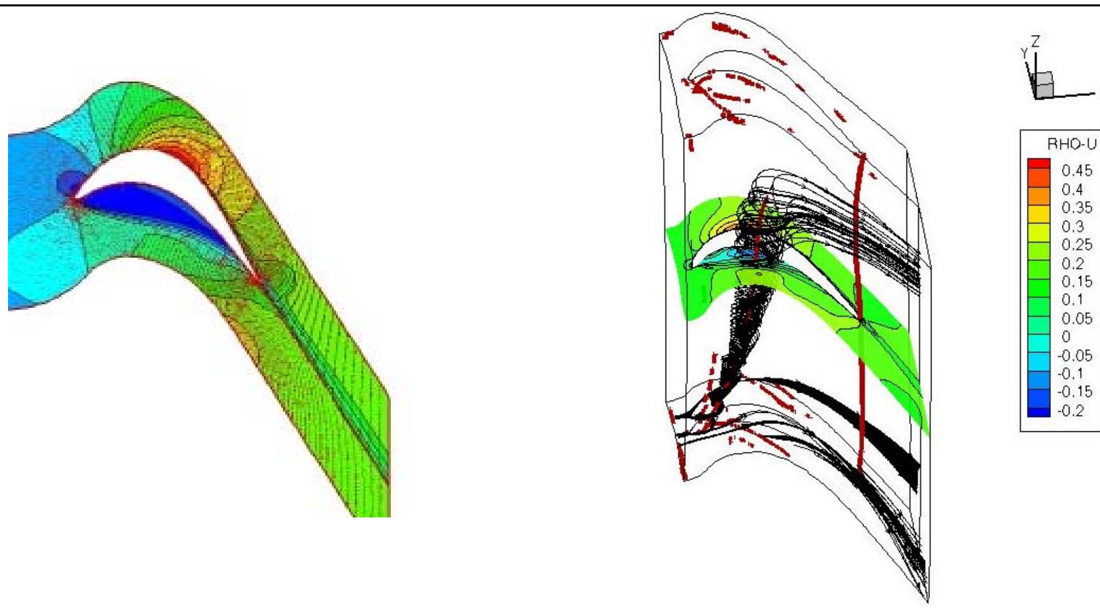
Figure 4. Contours of computed entropy for Stage 1 LCTR VSPT blading—(a) vane exit; (b) blade (rotor) exit; and (c) stage—showing regions of secondary-flow driven accumulation of aerodynamic blockage and loss.

3.2.2 3-D Flow Field at Off-design Operation

During off-design operation, the rotor blade rows (blades) of the VSPT operate at negative incidence as high at 50° to 55°. Management of loss levels associated with this large negative incidence is key to the viability of VSPT. Considering figure 3a, the 2-D profile loss at –55° for L1M blading appears to be acceptable; however, the loss bucket of figure 3a was constructed using 2-D computations. The impact of secondary flow fields (figure 4) due to turning and centripetal and Coriolis acceleration fields on loss production and transport is a key aspect in the management of loss production in subsequent blade rows (i.e., matching).

Two- and three-dimensional computational results are provided in figure 5. In figure 5a, Mach number contours reflect a 2-D separation region in the cove of the pressure side of the rotor (here the L1M rotor) at –55° of incidence. The separation benignly reattached before the trailing edge, even at this large incidence, and results in acceptable loss levels (figure 3a). In part, the low profile loss is due to the unloading of blade section at this high incidence; that is, although strongly off-design, the blade is affecting little blade turning. Unfortunately, the 2-D picture (figure 5a) is only a projection of the 3-D flow field (figure 5b) in which the cove separation is really part of a strong vortical flow structure that transports the low-momentum/high-entropy flow of the cove region outward toward the case. This transport has an associated aerodynamic blockage field that will impact subsequent matching with the downstream vane, exacerbating

off-design loss-levels. This result highlights the need to account for 3-D effects in the design and off-design analysis of the full multistage machine. This need, and the need to account for unsteady blade row interaction effects, has driven the approach taken within this project to use the ADS software and AFRL TDAAS Matlab scripts for the design/analysis of the VSPT.



a. Contours of computed Mach number at 100% N_{PT} (off-design) at mid-span from 2-D computation.

b. Streamlines and contours of computed rho-u 100% N_{PT} (off-design) at mid-span from 3-D computation.

Figure 5. Two- and three-dimensional computational results of example rotor flow fields at 100% N_{PT} off-design operation, showing 2-D and 3-D projections of pressure-side separation.

4. Next Steps: Experiments in Transonic Linear Cascade

Experimental testing of incidence-tolerant blading is scheduled for July 2011. The testing will be conducted in an existing transonic linear cascade at NASA Glenn Research Center, Cleveland, OH. The cascade has a unique capability for variations in Reynolds number, Mach number, and incidence over a range of relevance to the LCTR VSPT.

A transonic turbine cascade is being modified to extend the range of inlet air incidence angle that can be set when evaluating the performance of candidate blade shapes for VSPT designs. Figure 6 shows a view of the overall cascade, the inlet and discharge flow paths, and a table of key components.

Air enters the cascade through the upstream contraction (K), shown at the left side of figure 6. It is directed through the experimental blade row (D) by moveable upper and lower guide boards (A) and (F), and discharges through the exhaust duct on top of the cascade plenum. Air is pulled

through the cascade by a low-pressure exhaust source that is connected to the exhaust duct or is pushed through the cascade by high-pressure air that is made available at the cascade inlet. Reynolds number variation is achieved by throttling the cascade inlet. The incidence angle of the incoming air relative to the leading edge of the blade row is set by rotating disk (E), which contains the experimental blade row.

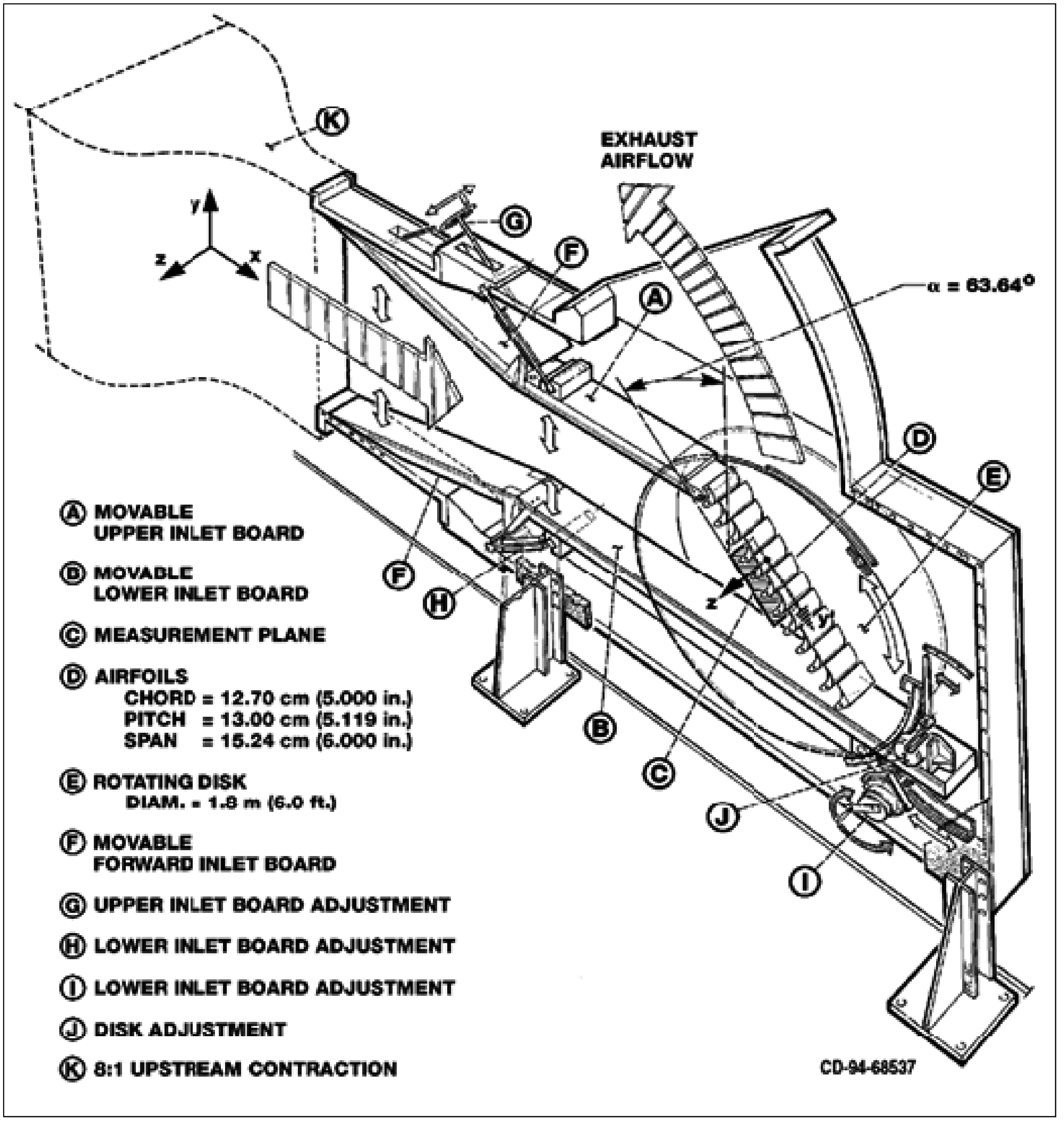


Figure 6. Transonic turbine cascade.

The range of incidence required for the VSPT blade tests, +5° to –55°, is outside of the range of the existing cascade configuration, which was established for high-pressure-turbine experiments. Figure 7 shows a side view of the flow path with the blade row set at a +40° incidence angle. Figure 8 shows the blade row position that will be required to produce a –55° incidence angle. To achieve the required range of incidence, modifications to the cascade are required. These modifications include changes to the disc turning mechanism and to the upper flow board, which must be extended to accomondate the increased rotational range.

Engineering design and fabrication planning for the needed improvements are underway.

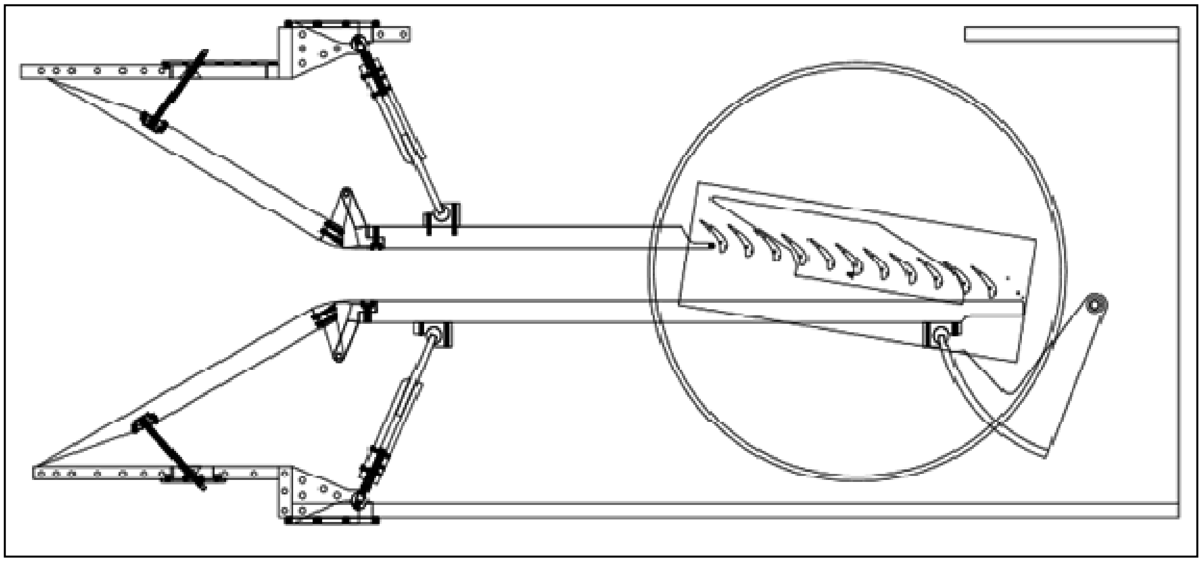


Figure 7. Cascade cross section at maximum positive incidence setting of +40°.

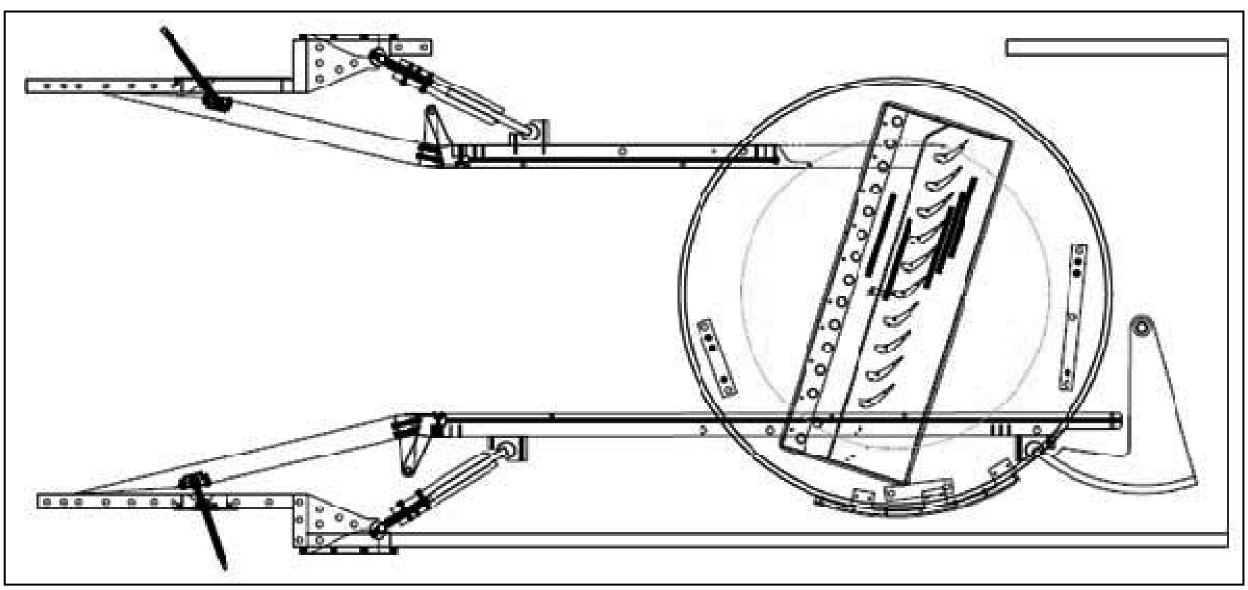


Figure 8. Cascade cross section at new maximum negative incidence setting of –55° (the previous capability was –5°).

5. Conclusions

Progress toward development and testing of incidence-tolerant blading for a VSPT capable of efficient operation with 50% speed change was described. Specific progress includes the following work elements:

- Validated a design-point mean-line turbine design code using available turbine efficiency experimental data to enable confident use of the design code for development of VSPT technology.
- Completed the conceptual aero-design of a four-stage VSPT; the technology is relevant to future Army rotorcraft (e.g., JMR).
- Completed the detailed aero-design of incidence-tolerant blading for rotor 1 of a four-stage turbine, and conducted preliminary 2-D and 3-D CFD work to assess incidence tolerance.
- In collaboration with NASA, the ARL DRI efforts have led to a NASA contract with Rolls-Royce North American Technologies for development of a conceptual design of a VSPT and the detailed blade design of incidence tolerant blading.
- In collaboration with NASA, the ARL DRI team has participated in the planning for a potential FY13 Aviation and Missile Research, Development and Engineering Center (AMRDEC)-AATD component test of VSPT technology.

Future steps to be taken under the NASA FAP/SRW program include the fabrication and instrumentation of incidence-tolerant blading for test in a transonic linear cascade over a range of Reynolds numbers, Mach numbers, and incidence of relevance to the VSPT of the LCTR application.

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7. Transitions

7.1 NASA Research and Technology for Aerospace Propulsion Systems (RTAPS) Contracts

The DRI provides complementary support to transition efforts conducted under the NASA FAP's SRW project via task order contracts with two engine companies:

- *Rolls-Royce North American Technologies and Rolls-Royce Corporation*: A two-month blade design contract to apply their experience with VSPT technology developed for the V-22 Osprey, as well as a proprietary blade design/optimization system to address the problem of a 50% variation in PT speed and Reynolds numbers between sea level to 35k ft. The deliverables were blade cross sections to test in-house in the transonic cascade.
- *Rolls-Royce North American Technologies and Rolls-Royce Corpo*ration: A six-month study contract to conduct conceptual design of a LCTR VSPT and delineate a cost-effective plan to design, fabricate, instrument, and test a VSPT component.
- *Williams International, L.L.C.*: A six-month study contract to conduct conceptual design of a LCTR VSPT and delineate a cost-effective plan to design, fabricate, instrument, and test a VSPT component.

7.2 American Helicopter Society Forum 66

Dr. Welch authored and presented a paper (Welch, 2010) in the propulsion session of the American Helicopter Society Forum 66 in May 2010.

7.3 Planned Army VSPT 6.2 Component Program

During the summer, the AATD, Ft. Eustis, VA, conducted a survey of four engine companies to gauge interest in a 6.2 component program for VSPTs. The companies each expressed a recognized growing need for the VSPT as an enabling technology for future Army VTOL aircraft (e.g., for JMR missions). AATD has expressed intent to initiate a 6.2 VSPT component development program in the FY13 timeframe. Dr. Welch and G. Skoch participated in five industry teleconferences/visits with AATD related to this survey. G. Welch provided input to K. Kerner of AATD during the survey formulation.

7.4 LPT Workshop

Dr. Welch participated in the development of an LPT workshop in August 2010. The workshop gathered industry experts from all major engine companies to discuss technical challenges and research needs for LPTs. Dr. Welch presented an overview of technical challenges and the NASA/ARL research approach for VSPTs.

7.5 Turbine Engine Technology Symposium Conference Workshop

Dr. Welch presented an overview of technical challenges and the NASA/ARL research approach for VSPTs at the Turbine Engine Technology Symposium in October 2010, Dayton, OH.

7.6 Discussion with the University of Notre Dame (UND)

The SRW VSPT has initiated discussions with the UND regarding potential testing of a VSPT component in the UND facility.

7.7 T700 Engine Test Potential

The question of finding the best venue to test rotating versions of VSPT designs was asked early on in collaboration with the NASA LCTR project. The existing T700 engine used by VTD to demonstrate compressor stall control technology was selected as a possible candidate. Contact was established with the engineering staff at General Electric (GE) Aircraft Engines, Lynn, MA, to discuss the potential for experiments using the existing T700 power turbine. The initial goal would be to obtain measurements for evaluating off-design performance predictions and it could be used later to evaluate new VSPT designs.

The conclusion reached through these talks is that power turbine experiments using the T700 are possible. A couple of issues with engine controls and power turbine shaft critical speed will have to be considered but the work is still doable. GE provided advice on PT instrumentation that is being applied to a preliminary experimental hardware design; engineering and fabrication analyses were completed.

A warm, single-spool turbine facility (W6) was recently modernized at the NASA Glenn Research Center that will be accessible by the VTD field element. The facility could test new rotor designs that may have lower fabrication costs than rotors for an engine test. The facility could also provide a greater Reynolds number range than the T700 test stand. However, the lead-time preceding any experimentation will be longer because a test rotor must be fabricated.

A low-temperature, low-speed, low-cost turbine facility is also available at UND and it may be a candidate for rotating tests. The rotors are fabricated from aluminum, so time and cost are minimized. The facility may be best for blade surface transition studies. The VTD/NASA team is planning to visit the UND turbine facility.

List of Symbols, Abbreviations, and Acronyms

2-D	two- dimensional
3-D	three-dimensional
AATD	Aviation Applied Technology Directorate
ADS	AeroDynamics Solutions, Inc.
AFRL	Air Force Research Laboratory
AMDCKO	Ainley and Mathieson (1957), Dunham and Came (1970), and Kacker and Okapuu (1982)
AMRDEC	Aviation and Missile Research, Development and Engineering Center
ARL	U.S. Army Research Laboratory
CFD	computational fluid dynamic
DOE	Department of Energy
DRI	Director’s Research Initiative
FAP	Fundamental Aeronautics Program
FATE	Future Affordable Turbine Engine
FY	fiscal year
GE	General Electric
GRAPE	Grids About Airfoils Using Poisson’s Equation
HETR	Army Highly Efficient Tilt Rotor
JMR	Joint Multi-Role
LCTR	Large Civil Tilt Rotor
LPT	low-pressure turbine
NASA	National Aeronautics and Space Administration
NURBS	non-uniform rational b-spline
PT	power turbine
RANS	Reynolds-Averaged Navier-Stokes

SHP	shaft horse-power
SLS	sea-level-static
SRW	Subsonic Rotary Wing
TCGRID	Turbomachinery C-GRID
TDAAS	Turbine Design and Analysis System
UND	University of Notre Dame
VSPT	variable-speed power turbine
VTD	Vehicle Technology Directorate
VTOL	vertical takeoff and landing
W6	warm, single-spool turbine facility

Glossary

AN^2	=	product of annulus area and rpm-squared
c_x	=	axial chord
h_0, h	=	total and static specific enthalpy
i, i_s	=	incidence, incidence at suction-side stall
M, M_r	=	absolute and relative Mach numbers
N_{PT}	=	power-turbine shaft speed, rpm
p_0, p	=	total and static pressure
R_{ecx}	=	Reynolds number based on axial chord
s	=	blade pitch
u	=	(u_x, u_θ), absolute velocity
U	=	rotor speed at pitchline
w	=	$(u_x, u_\theta - U)$, relative velocity
Z	=	$\frac{s}{c_x}\frac{\rho u_x(u_{\theta,1}-u_{\theta,2})}{p_{0,r,1}-p_2}$, Zweifel loading parameter
η_{stg}	=	stage efficiency (total-to-total)
ρ	=	density
ψ	=	$\Delta h_0/U^2$, work factor
φ	=	u_x/U, flow coefficient

Subscripts

c	=	corrected condition
4.5	=	power turbine inlet

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